Is SAX J1808.4-3658 A Strange Star?

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One of the most important questions in the study of compact objects is the nature of pulsars, including whether they are composed of β-stable nuclear matter or strange quark matter. Observations of the newly discovered millisecond X-ray pulsar SAX J1808.4-3658 with the Rossi X-Ray Timing Explorer place firm constraint on the radius of the compact star. Comparing the mass - radius relation of SAX J1808.4-3658 with the theoretical mass - radius relation for neutron stars and for strange stars, we find that a strange star model is more consistent with SAX J1808.4-3658, and suggest that it is a likely strange star candidate.

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The transient X-ray burst source SAX J1808.4-3658 was discovered in September 1996 with the Wide Field Camera (WFC) on board BeppoSAX [1]. Two bright type I X-ray bursts were detected, each lasting less than 30 seconds. Such bursts are generally accepted to be due to thermonuclear flashes on the surface of a neutron star [2], suggesting that this source is a member of low-mass X-ray binaries (LMXBs), consisting of a low ($\lesssim 10^{10}$ G) magnetic field neutron star accreting from a companion star of less than one solar mass [3]. Analysis of the bursts in SAX J1808.4-3658 indicates that it is 4 kpc distant and has a peak X-ray luminosity of $6\times10^{36}\,\mathrm{erg\,s^{-1}}$ in its bright state, and $<10^{35}\,\mathrm{erg\,s^{-1}}$ in quiescence [1].

Recently a transient X-ray source designated XTE J1808-369 was detected with the Proportional Counter Array (PCA) on board the Rossi X-ray Timing Explorer (RXTE) [4]. The source is positionally coincident within a few arcminutes with SAX J1808.4-3658, implying that both sources are the same object. Coherent pulsations at a period of 2.49 milliseconds were discovered [5]. The star's surface dipolar magnetic moment was derived to be $\lesssim 10^{26}\,\mathrm{G\,cm^3}$ from detection of X-ray pulsations at a luminosity of $10^{36}\,\mathrm{erg\,s^{-1}}$ [5], consistent with the weak fields expected for type I X-ray bursters [2] and millisecond radio pulsars (MS PSRs) [3]. The binary nature of SAX J1808.4-3658 was firmly established with the detection of a 2 hour orbital period [6], as well as with the optical identification of the companion star [7]. SAX J1808.4-3658 is the first pulsar to show both coherent pulsations in its persistent emission and thermonuclear bursts, and by far the fastest-rotating, lowest-field accretion-driven pulsar known. It presents direct evidence for the evolutionary link between LMXBs and MS PSRs [3].

The discovery of SAX J1808.4-3658 also allows a direct test of the compactness of pulsars. Detection of X-ray pulsations requires that the inner radius R_0 of the accretion flow (generally in the form of a Keplerian accretion disk in LMXBs) should be larger than the stellar radius R (viz. the stellar magnetic field must be strong enough to disrupt the disk flow above the stellar surface), and less than the so-called corotation radius $R_\mathrm{c}=[GM/(4\pi^2)P^2]^{1/3}$ (viz. the stellar magnetic field must be weak enough that accretion is not centrifugally inhibited) [8,9]. Here G is the gravitation constant, M is the mass of the star, and P is the pulse period. The inner disk radius R_0 is generally evaluated in terms of the Alfvén radius R_A, at which the magnetic and material stresses balance [3], $R_0=\xi R_\mathrm{A}=\xi[B^2R^6/\dot{M}(2GM)^{1/2}]^{2/7}$, where B and $\dot{M}$ are respectively the surface magnetic field and the mass accretion rate of the pulsar, and ξ is a parameter of order of unity almost independent of $\dot{M}$ [8,10]. Since X-ray pulsations in SAX J1808.4-3658 were detected over a wide range of mass accretion rate, say, from $\dot{M}_{\rm min}$ to $\dot{M}_{\rm max}$, a firm upper limit of the stellar radius can then be obtained from the condition $R < R_0(\dot{M}_{\rm max}) < R_0(\dot{M}_{\rm min}) < R_{\rm c}$, i.e.,

$$R < 27.6(\frac{F_{\rm max}}{F_{\rm min}})^{-2/7}(\frac{P}{2.49\,{\rm ms}})^{2/3}(\frac{M}{M_\odot})^{1/3}\,{\rm km}, \quad (1)$$

where $F_{\rm max}$ and $F_{\rm min}$ denote the X-ray fluxes measured during X-ray high- and low-state, respectly, $M_\odot$ is the solar mass. Here we have assumed that the mass accretion rate $\dot{M}$ is proportional to the X-ray flux observed with RXTE. This is guaranteed by the fact that the X-ray spectrum of SAX J1808.4-3658 was remarkably stable [11] and there was only slightly increase in the pulse amplitude [12] when the X-ray luminosity varied by a factor of ~ 100 during the 1998 April/May outburst.

Given the range of X-ray flux at which coherent pulsations were detected, inequality (1) defines a limiting curve in the mass - radius ($M-R$) parameter space for SAX J1808.4-3658, as plotted in the dashed curve in Fig. 1. During the 1998 April/May outburst, the maximum observed $2-30$ keV flux of SAX J1808.4-3658 at the peak of the outburst was $F_{\rm max} \simeq 3\times10^{-9}\,{\rm erg\,cm^{-2}\,s^{-1}}$, while the pulse signal became barely detectable when the flux dropped below $F_{\rm min} \simeq 2\times10^{-11}\,{\rm erg\,cm^{-2}\,s^{-1}}$ [12]. Here we adopt $F_{\rm max}/F_{\rm min} \simeq 100$. The dotted curve represents the Schwarzschild radius $R = 2GM/c^2$ (where c is the speed of light) - the lower limit of the stellar radius to prevent the star collapsing to be a black hole [13]. Thus the allowed range of the mass and radius of SAX J1808.4-3658 is the region confined by the dashed and dotted curves in Fig. 1.

Figure 1 compares the theoretical $M-R$ relations (solid curves) for nonrotating neutron stars given by six recent realistic models for the equation of state (EOS) of dense matter. In models UU [14], BBB1 and BBB2 [15] the neutron star core is assumed to be composed by an uncharged mixture of neutrons, protons, electrons and muons in equilibrium with respect to the weak interaction (β-stable nuclear matter). Equations of state UU, BBB1, BBB2 are based on microscopic calculations of asymmetric nuclear matter by use of realistic nuclear forces which fit experimental nucleon-nucleon scattering data, and deuteron properties. In model Hyp [16], hyperons are considered in addition to nucleons as hadronic constituents of the neutron star core. Next, we consider, as a limiting case, a very *soft* EOS for β-stable nuclear matter, namely the BPAL12 model [16], which is still able to sustain the measured mass 1.442 $M_\odot$ of the pulsar PSR 1916+13. In general, a *soft* EOS is expected to give a lower limiting mass and a smaller radius with respect to a *stiff* EOS [13]. Finally, we consider the possibility that neutron stars may possess a core with a Bose–Einstein condensate of negative kaons [17–19]. The main physical effect of the onset of K^- condensation is a softening of the EOS with a consequent lowering of the neutron star maximum mass and possibly of the radius. Actually, neutron star with $R \sim 7-9$ *km* were obtained [18,19], for some EOS with K^- condensation. However, in those models [18,19] the kaon condensation phase transition was implemented using the Maxwell construction, which is inadequate in stellar matter, where one has two conserved charges: baryon number and electric charge [20]. When the kaon condensation phase transition is implemented properly [20], one obtains neutron stars with "large" radii, as shown by the curve labeled K^- in Fig. 1. Moreover, kaon-nucleon and nucleon-nucleon correlations rise the threshold density for the onset of kaon condensation, possibly to densities higher than those found in the centre of stable neutron stars [21]. It is clearly seen in Fig. 1 that none of the neutron star $M-R$ curves is consistent with SAX J1808.4-3658 (Including rotational effects will shift the $M-R$ curves to up-right in Fig. 1 [22], and does not help improve the consistency between the theoretical neutron star models and observations of SAX J1808.4-3658). Moreover, it is unlikely that the actual mass and radius of SAX J1808.4-3658 lie very close to the dashed curve, since the minimum flux $F_{\rm min}$ at which X-ray pulsations were detected by RXTE was determined by the instrumental sensitivity, and the actual value could be even lower; while the presence of the slight X-ray dips observed in SAX J1808.4-3658 [6] suggests that the companion mass is most likely to be less than $0.1M_\odot$, and the pulsar mass op more than $1M_\odot$. Therefore it seems that SAX J1808.4-3658 is not well described by a neutron star model. As shown below, a strange star model seems to be more compatible with SAX J1808.4-3658.

Note that in writing inequality (1) we have implicitly assumed that the pulsar magnetic field is basically dipolar, even when the accretion disk is close to the stellar surface. This is partly supported by the agreement between the dipolar spin-up line and the location of MS PSRs in the spin period - spin period derivative diagram, which implies that the multipole moments in LMXBs are no more than $\sim 40\%$ of the dipole moments if the quadrupole component is comparable to or larger than higher order anomalies [25]. However, the $R_0(\dot{M})$ relation will be changed if the star's field has more complicated structure. For example, there may exist regions on the surface of the star where the magnetic field strength is much greater than that from a central dipole, to affect the channelling of the accretion flow and the pulsed emission; the induced current flow in the boundary layer of the disk could increase the field strength when R_0 reaches R. If SAX J1808.4-3658 possesses such anomalous field, there should be two kinds of observational effects: the pulse profile shows a dependence on energy (because in strongly magnetized plasma, photons with different energies have different scattering cross-sections), and the X-ray spectrum changes with the mass accretion rate (due to a change in the configuration of accretion pattern and in the X-ray emitting region). These are in contrast with the observations of SAX J1808.4-3658, which shows a single sine pulse profile with little energy dependence [12], and stable X-ray spectra when the X-ray luminosity varied by a factor of ~ 100 [11]. Note also that in the $R_0(\dot{M})$ formula the parameter $\xi \sim R_0/h$, where h is the scale height of the disk [24]. The effect of the increase in B_r with $\dot{M}$, due to the induced current, may be largely counteracted by the decrease of ξ with $\dot{M}$, and a steeper $\dot{M}$-dependence of R_0 when the effect of general relativity is included [23]. So we conclude that the accretion flow around SAX J1808.4-3658 may still be dominated by a central dipole field even when the disk reaches the star.

Strange stars are astrophysical compact objects which are entirely made of deconfined u,d,s quark matter (*strange matter*). The possible existence of strange stars is a direct consequence of the conjecture [26] that strange matter may be the absolute ground state of strongly interacting matter. Detailed studies have shown that the existence of strange matter is allowable within uncertainties inherent in a strong interaction calculation [27]; thus strange stars may exist in the universe. Apart from the fact that strange stars may be relics from the cosmic separation of phases as suggested by Witten [26], a seed of strange matter may convert a neutron star to a strange one [28]. Conversion from protoneutron stars during the collapse of supernova cores is also possible [29]. Recent studies have shown that the compact objects associated with the X-ray pulsar Her X-1 [30,31], and with the X-ray burster 4U 1820-30 [32], are good strange star candidates.

Most of the previous calculations [33] of strange star properties used an EOS for strange matter based on the phenomenological nucleonic bag model, in which the basic features of quantum chromodynamics, such as quark confinement and asymptotic freedom are postulated from the beginning. The deconfinement of quarks at high density is, however, not obvious in the bag model. To find a star of small mass and radius, one has to postulate a large bag constant, whereas one would imagine in a high density system the bag constant should be lower.

Recently, Dey *et al.* [31] derived an EOS for strange matter, which has asymptotic freedom built in, shows confinement at zero baryon density, deconfinement at high density, and gives a stable configuration for chargeless, β-stable strange matter. In this model the quark interaction is described by an interquark vector potential originating from gluon exchange, and by a density dependent scalar potential which restores the chiral symmetry at high density. This EOS was then used [31] to calculate the structure of strange stars. Using the same model (but different values of the parameters with respect to those employed in ref. [31]) we calculated the $M-R$ relations, which are also shown in solid curves labeled ss1 and ss2 in Fig. 1, corresponding to strange stars with maximum masses of $1.44\,M_\odot$ and $1.32\,M_\odot$ [35] and radii of 7.07 km and 6.53 km, respectively. It is seen that the region confined by the dashed and dotted curves in Fig. 1 is in remarkable accord with the strange star models. Figure 1 clearly demonstrates that a strange star model is more compatible with SAX J1808.4-3658 than a neutron star one.

If SAX J1808.4-3658 is a strange star, then the thermonuclear flash model [2] can not be invoked to explain the observed X-ray bursts. However, a different mechanism has been recently proposed [36], in which the X-ray burst is powered basically by the conversion of the accreted normal matter to strange quark matter on the surface of a strange star.

As both the spin rate and the magnetic moment of SAX J1808.4-3658 resemble those inferred for other, non-pulsing LMXBs, an interesting and important question is: why is SAX J1808.4-3658 the only known LMXB with an MS PSR? The most straightforward explanation seems to be that the magnetic field of SAX J1808.4-3658 is considerably stronger than that of other systems of similar X-ray luminosity [5]. We point out that a strange star is more liable to radiate pulsed emission than a neutron star because of its compactness. As seen in Fig. 1, the radius of a $\sim 1\,M_\odot$ strange star is generally $1.5-2$ times smaller than that of a neutron star of similar mass, implying that, with the same magnetic moment (the observable quantity), the surface field strength of the strange star is $3-8$ times higher than that of the neutron star, and that the size of the polar caps in the strange star for field-aligned flow, $4\pi R^2(1-(1-R/R_0)^{1/2})$, is up to 10 times smaller than in the neutron star. The more efficient magnetic channelling of the accreting matter close to the strange star surface could then lead to higher pulsation amplitudes, making it easier to detect. A strange star model for SAX J1808.4-3658 may also help to explain the unusually hard X-ray spectrum [11], if it has a low-mass ($\sim 10^{-20}-10^{-19}\,M_\odot$) atmosphere [37].

Strange stars have been proposed to model γ-ray bursters [34], soft γ-ray repeaters [38] and the bursting X-ray pulsar GRO J1744-28 [36]. But these models are generally speculative. In this work, we have suggested that SAX J1808.4-3658 is a likely strange star candidate, by comparing its $M-R$ relation determined from X-ray observations with the theoretical models of a neutron star and of a strange star. If so, there will be very deep consequences for both the physics of strong interactions and astrophysics. But we point out that the available observational data are not sufficient and accurate enough to exclude the possibility that SAX J1808.4-3658 could be a neutron star with anomalous magnetic fields. It has been suggested that strange stars could become unstable to $m=2$ bar mode [39]. Further observations of this signature in case of SAX J1808.4-3658 will be of great interest.

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[35] Strange stars (if they exist in the Universe, as we claim in the present manuscript) represent a new class of astrophysical compact objects, and their existence does not exclude the existence of neutron stars. Consequently, neutron stars and strange stars have two different values of the Oppenheimer-Volkoff maximum mass. If the compact object in PSR1913+16 is a neutron star, then its measured mass does not constraint the value $M_{max}(SS)$ of the maximum mass of a strange star. Therefore, the possible inequality $M_{max}(SS) < 1.44 M_{\odot} < M_{max}(NS)$ is not in contrast with observational data on compact objects masses.
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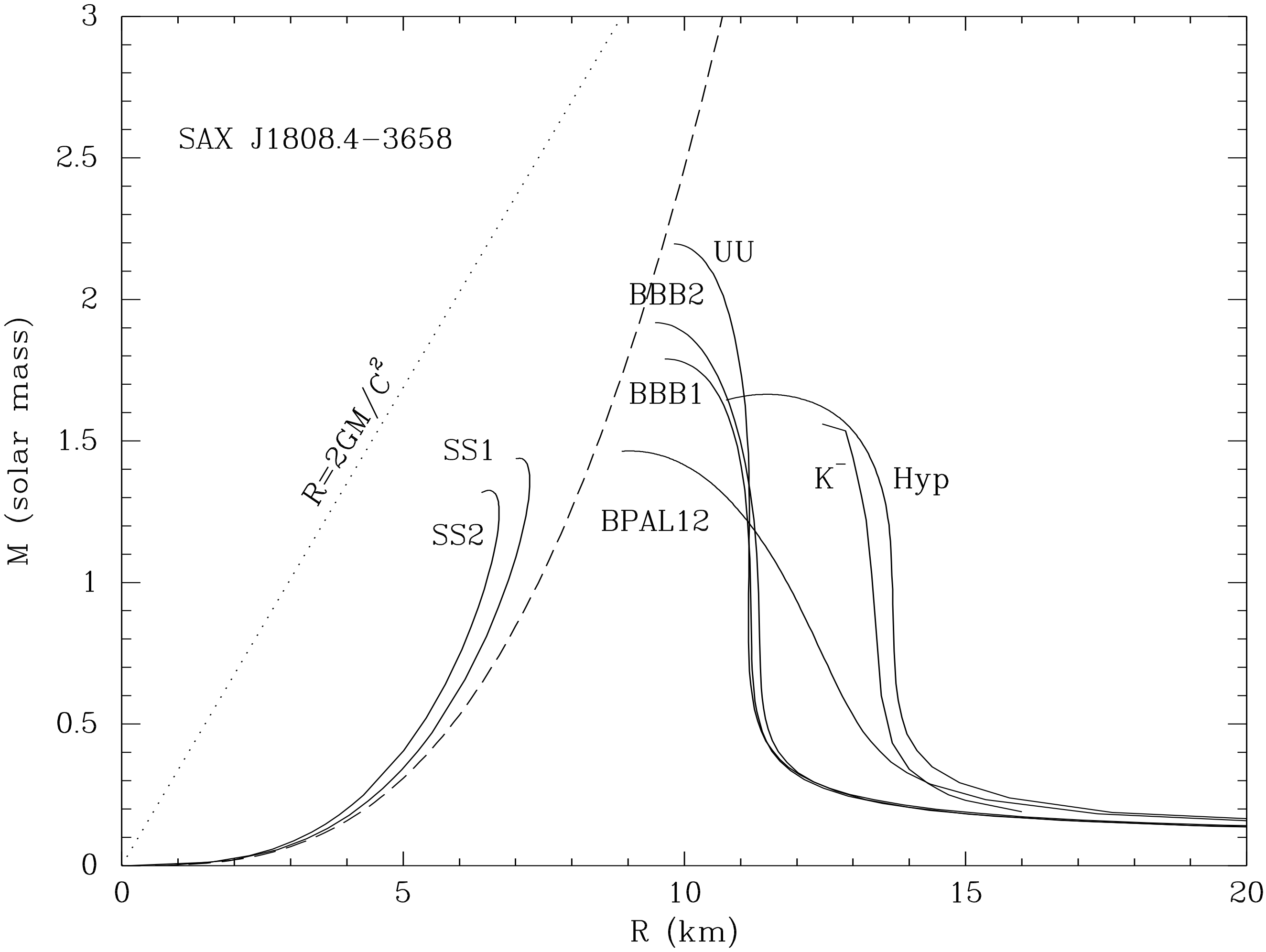
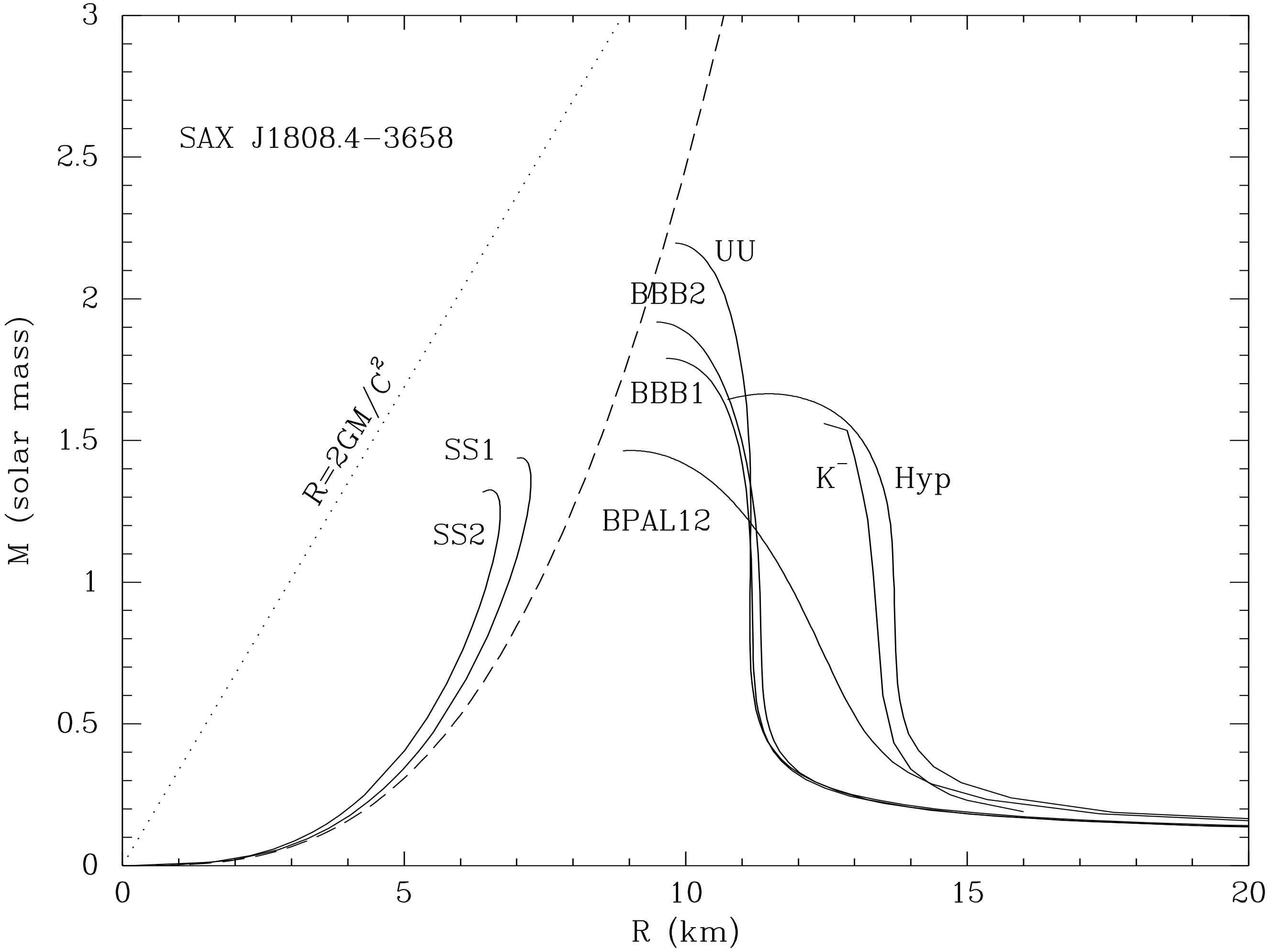


FIG. 1. Comparison of the $M-R$ relation of SAX J1808.4-3658 determined from RXTE observations with theoretical models of neutron stars and of strange stars. The range of mass and radius of SAX J1808.4-3658 is allowed in the region outlined by the dashed and dotted curves. The solid curves labeled UU, BBB1, BBB2, BPAL12, hyp, and K^- represent various $M-R$ relations for *realistic* EOSs of nonrotating neutron stars; the solid curves labeled ss1 and ss2 are for strange stars (see text for details and references to the EOS models). It is obvious that strange stars are more consistent with the SAX J1808.4-3658 properties compared to neutron stars.


SAX J1808.4−3658
R=2GM/C²
SS1
SS2
UU
BBB2
BBB1
BPAL12
K⁻
Hyp
M (solar mass)
R (km)
0
0.5
1
1.5
2
2.5
3
5
10
15
20